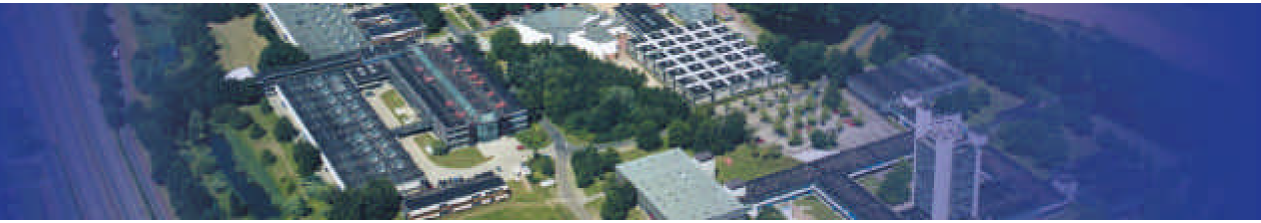


Recent developments in the Dutch Laser Wakefield Accelerators program at the University of Twente:

New external bunch injection scheme.

A.G. Khachatryan, F.A. van Goor, J.W.J. Verschuur and K.-J. Boller

University of Twente, Enschede, The Netherlands.

ELAN Hamburg November 2-5, 2004

Dutch Laser Wakefield Accelerators Program

University of Twente
Laser Physics group

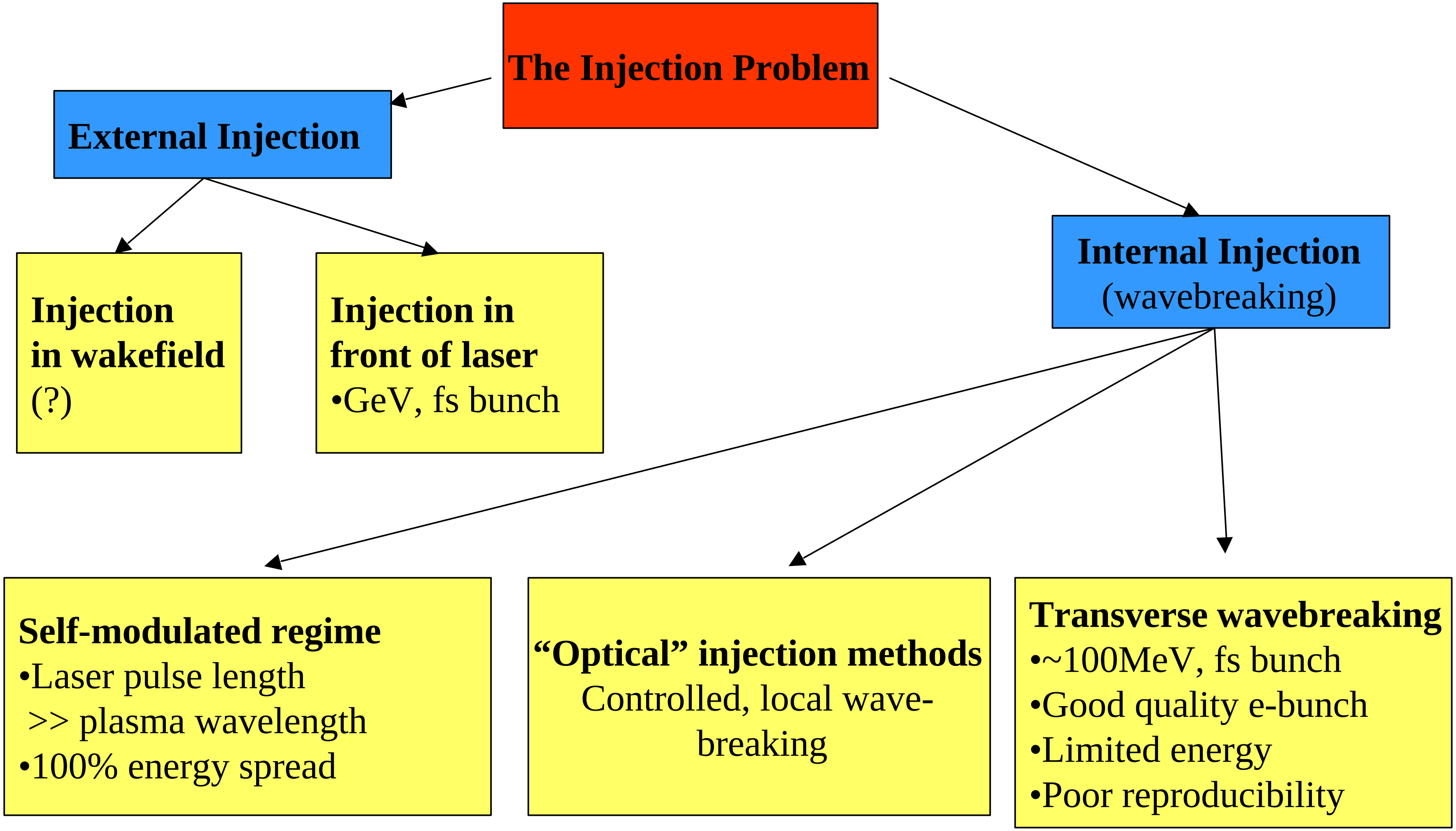
University of Eindhoven
Physics and Applications of Ion Beams and Accelerators group

FOM-Institute for Plasma Physics "Rijnhuizen"
Laser-Plasma XUV Source and XUV optics group

Support and Topics

- Foundation for Fundamental Research on Matter (FOM)
- Project duration: 2002 - 2008
- External injection schemes (TUE, UT)
- Photo injector (TUE, UT)
- Ti-Sapphire laser (UT)
- Plasma channel (FOM-Rijnhuizen)

LWFA

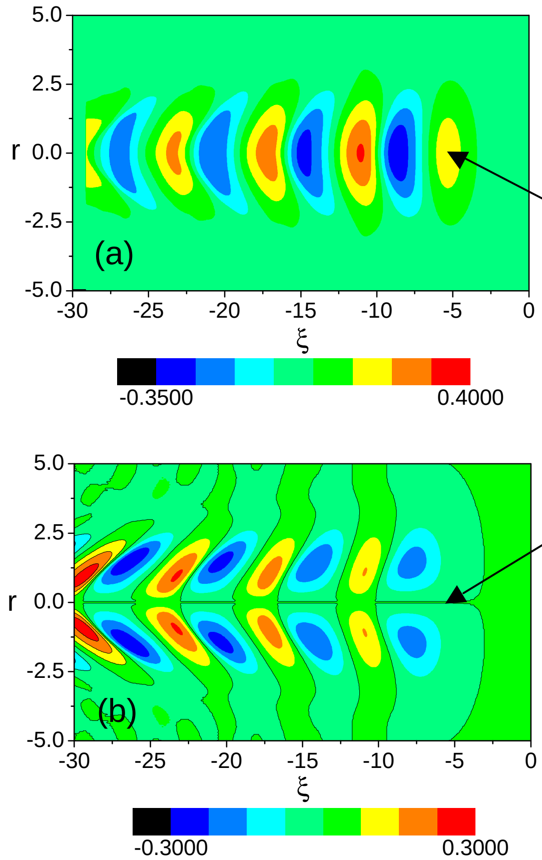


The Injection Problem
External Injection
Injection in wakefield (?)
Injection in front of laser
•GeV, fs bunch
Internal Injection (wavebreaking)
Self-modulated regime
•Laser pulse length >> plasma wavelength
•100% energy spread
"Optical" injection methods
Controlled, local wave-breaking
Transverse wavebreaking
•~100MeV, fs bunch
•Good quality e-bunch
•Limited energy
•Poor reproducibility

Laser Wakefields in Plasma Channel

Longitudinal wakefield

Transverse wakefield



Accelerating:

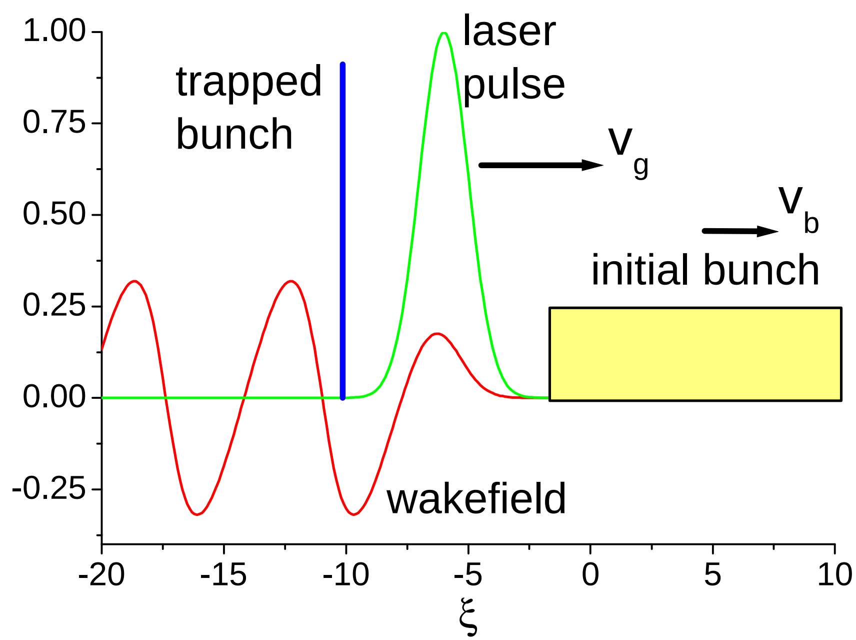
Decelerating:

Position of laser pulse

Focusing:

Defocusing:

Novel e-bunch Injection Scheme



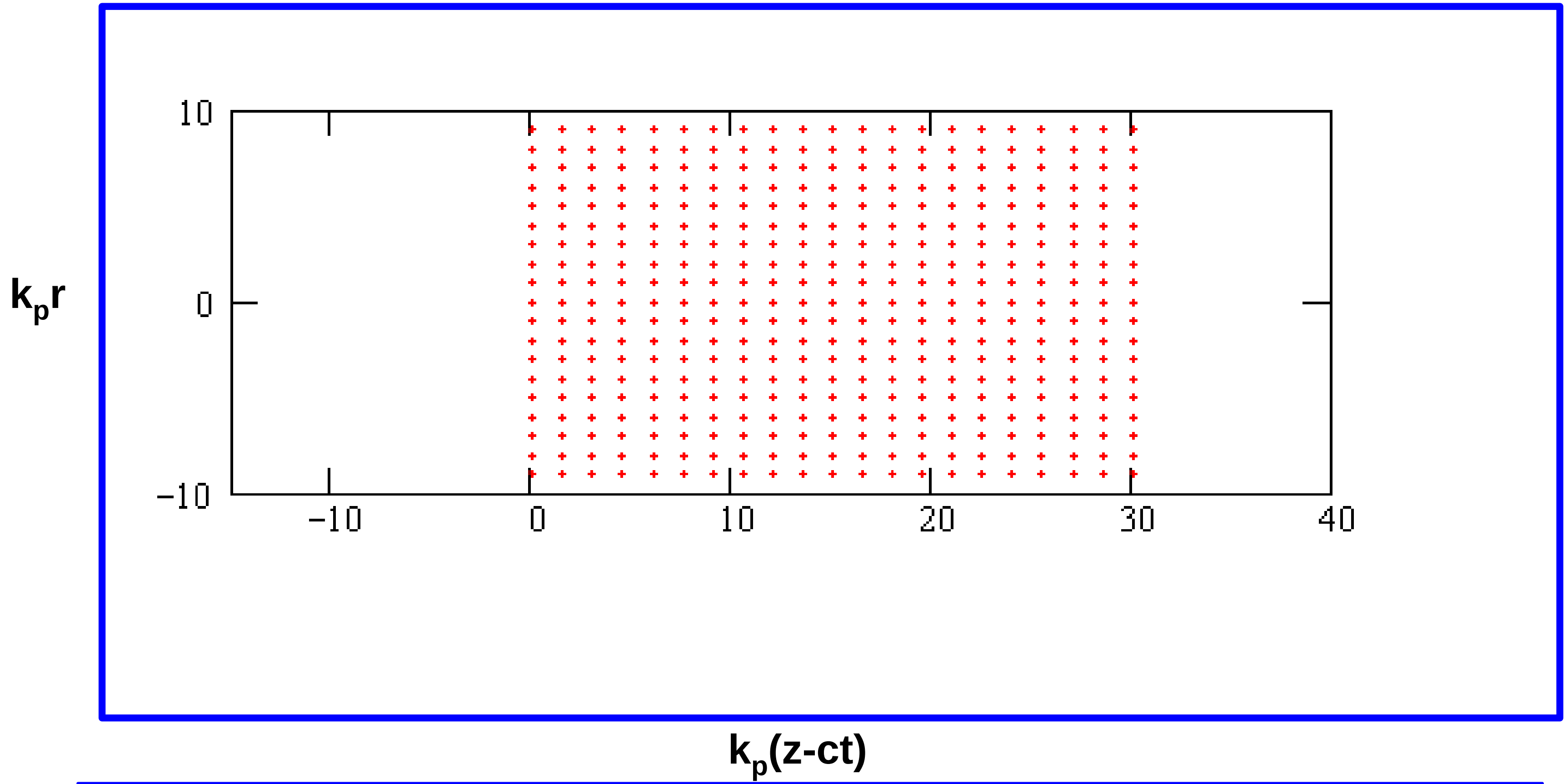
Publications on the scheme:

A.G. Khachatryan , F.A. van Goor, K.-J. Boller, *Proceedings PAC'03,* pp.1900-1902 (2003).

A.G. Khachatryan, *Phys. Rev. E* 65, 046504 (2002).

A.G. Khachatryan, *JETP Letters* 74, 371 (2001).

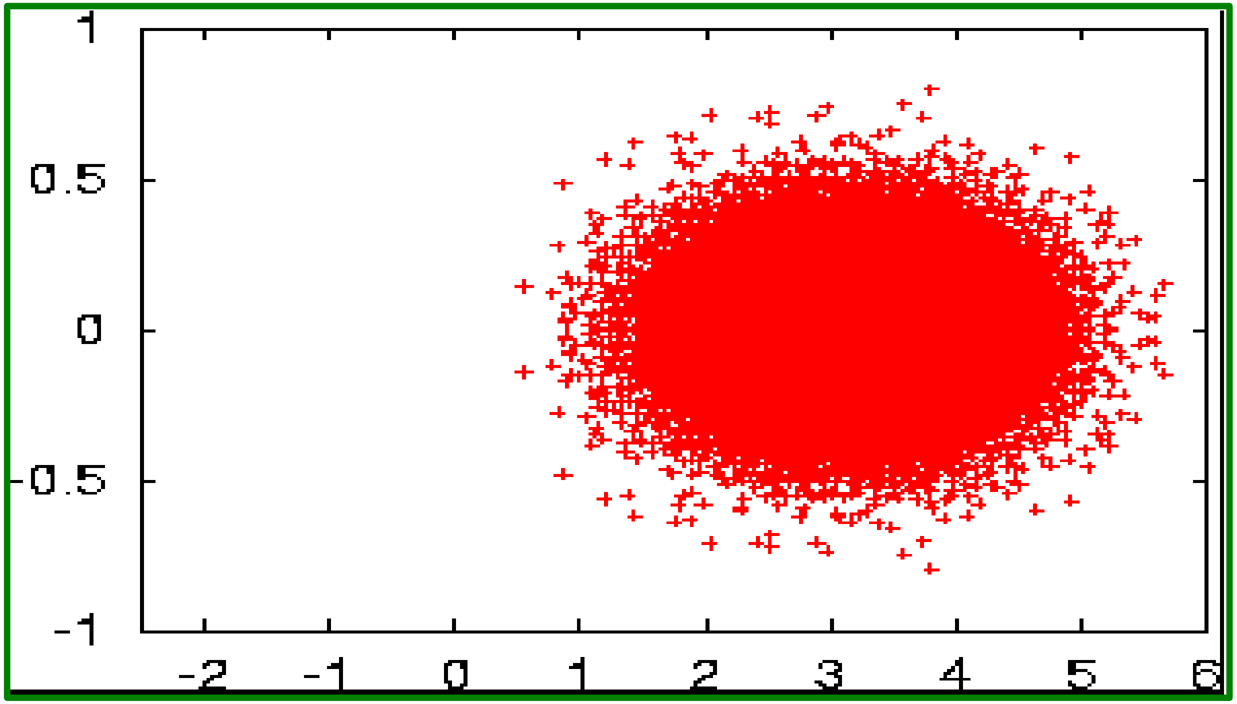
How it works



Initial parameters of the bunch: length - 4.8 l_p; energy ($mc^2\gamma$) – 1.14 MeV.

The trapped bunch length: $l_p/57$; radius: $l_p/7$; it is accelerated to ~600 MeV on a distance of ~1 cm.

How it works - II



Another example with 30000 electrons.

A. Reitsma, University of Strathclyde, Glasgow

The New Scheme

Low-energy electron bunch:

•Energy (γ_0) – hundreds keVs to few MeVs

•Length (L_0) – up to a few hundreds microns

•Trapping distance: $L_{tr} \sim 2\, \gamma_0^2 L_0$

+

Plasma channel

Parabolic radial density profile, $n_p \sim 10^{17}$-10^{18} cm^{-3}.

+

High-intensity laser pulse:

•Intensity >10^{18} W/cm^2

=

Ultra-short relativistic electron bunch:

•Length – ~ 1 micron (few *fs*);

•Diameter – few microns;

•Energy – up to a few GeV's;

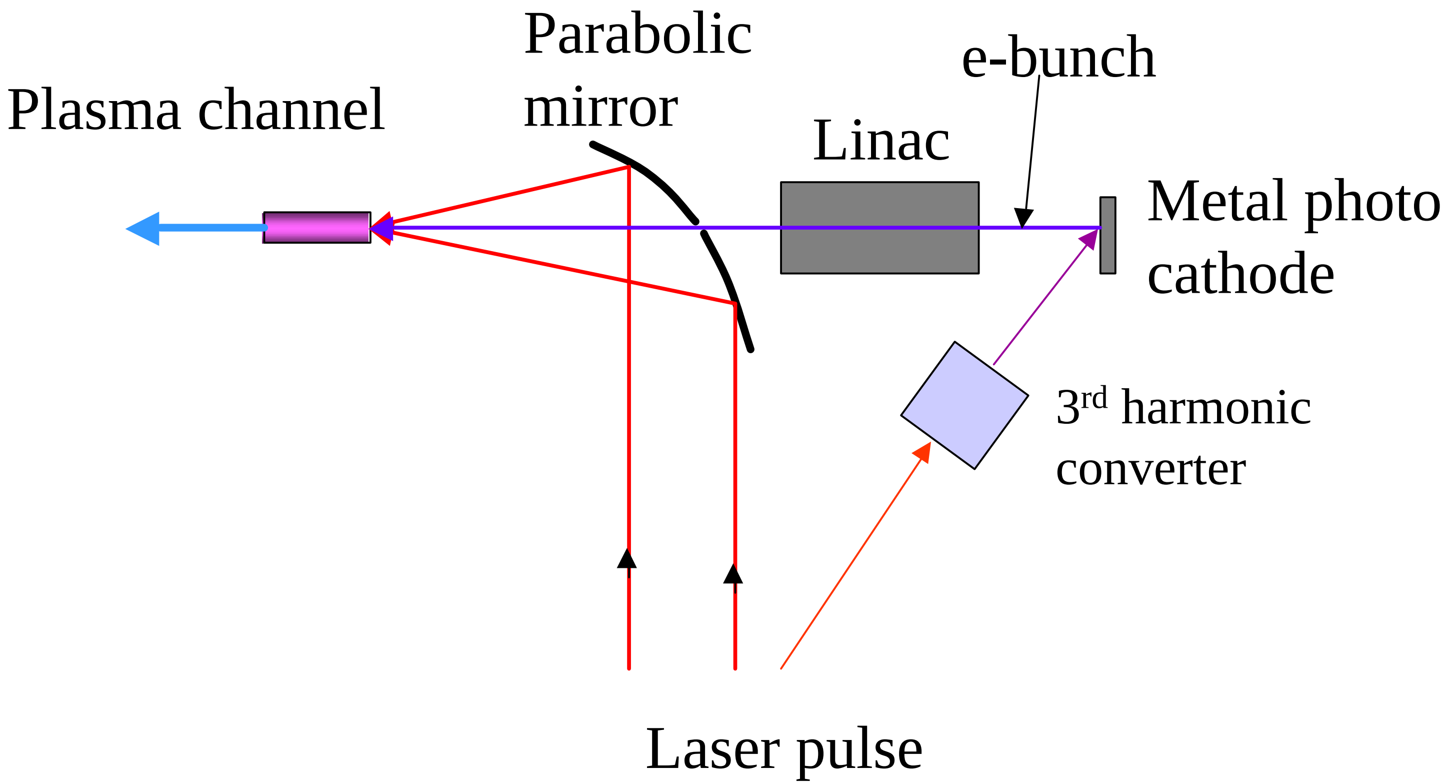
•Number of electrons – ~10^8 (~10 pC);

• Emittance – ~0.1 mm mrad.

Advantages of the LWFA scheme

- No ultra-short electron bunch is needed before the acceleration in the laser wakefield;
- No femtosecond synchronization is required while injecting the bunch in the wakefield;
- No transverse size of a few micron and precise transverse positioning are needed for the injecting e-bunch;
- Effective longitudinal and transverse electron-bunch compression;
- Good quality of the accelerated bunch;
- Scaling to high energies (GeV's) is possible.

Experimental Set-Up



Parameters for Proof-of-Principle Experiment with ~1J, (30-50) fs Laser Pulse.

University of Twente
The Netherlands

Laser pulse:	Wavelength: 0.8 μm Peak intensity at focus: (1–6)×10^{18} W/cm^2 Normalized amplitude, a_0: 0.7–1.7 σ_z: 7.65-12.75 μm σ_r: 20-50 μm
Plasma channel:	On-axis electron concentration, $n_p(0)$: (0.7–2) ×10^{18} cm^{-3} On-axis plasma wavelength, λ_p: (24–40) μm Channel length: (2–5) cm
Injected electron bunch:	Energy $m_e c^2 \gamma_0$: (1–4) MeV Bunch duration: (200–700) fs Bunch diameter: (100–200) μm Number of electrons: 10^8–10^9 ((16–160) pC)
Accelerated electron bunch:	Energy $m_e c^2 \gamma_0$: (0.2–4.5) GeV Bunch duration: (1–10) fs Bunch diameter: (2–10) μm Number of electrons: up to 10^8 (16 pC) – beam loading limit

Conclusion

New external injection scheme promises electron bunch generation with:

- **High quality;**
- **High energy (GeV’s);**
- **Extremely short duration (fs).**

End

Mathematical and numerical approaches

Laser pulse

- Gaussian 3D pulse which is assumed to be non-evolving
- Ponderomotive force acting on plasma electrons, F_p~ Ñ *I*

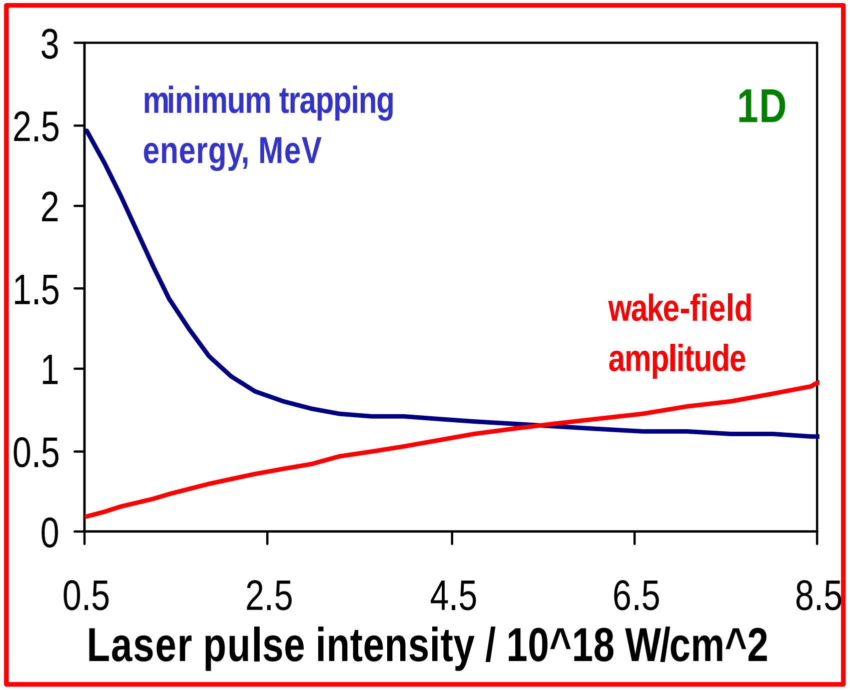
Electron bunch

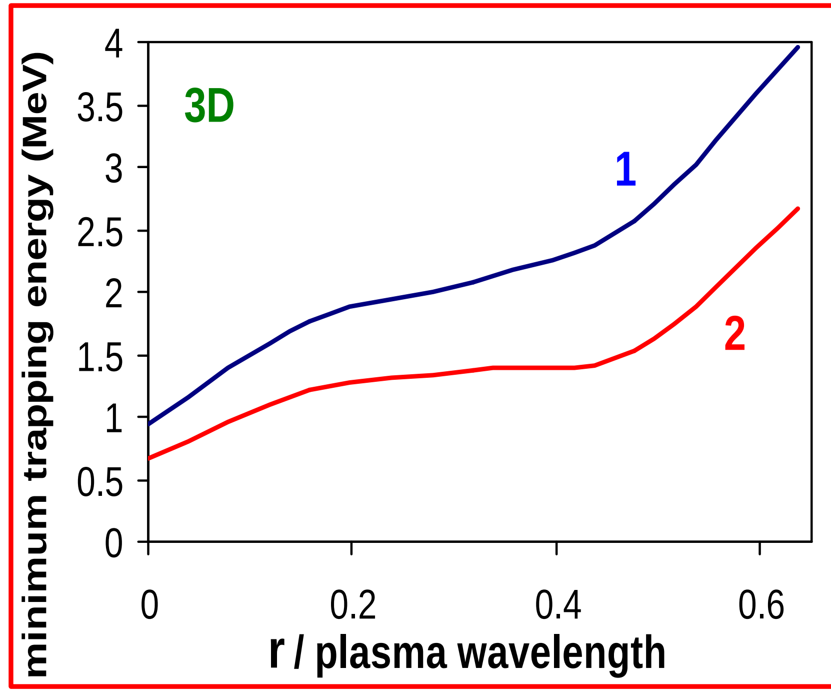
- Relativistic equation of motion for bunch electrons
- Maxwell equations for plasma wake-field calculations

Plasma

- Maxwell equations for laser wake-field calculations
- Continuity equation and
- Relativistic equation of motion for plasma electrons
- Ions are immobile
- The plasma is cold

Trapping conditions





Minimum trapping energy

and wake amplitude in 1D.

Minimum trapping energy depending on initial radial position,

1 – $I_0=2.1\times 10^{18}$ W/cm^2; 2 – $I_0=4.75\times 10^{18}$ W/cm^2.

$$\gamma_{min}<\gamma_{tr}<\gamma_g\approx l_p/\,l_L>>1$$

? **The minimum trapping energy:** $g_{\min} \approx |f_{min} + 1/f_{min}|/2$.

? **The trapping distance for an e-bunch**: $l_{tr} \approx 2 g_0^2 L_0$, L_0 is the initial bunch length.

? **The normalised emittance:** $e_n \sim (R^2 W / 4 p^2)\, l_p$,

$W = (|¶f_r/\partial r|/g)^{1/2}$ is the betatron frequency, $R << s_r$ is the trapped bunch radius, W and R are in the normalized units; $e_n \sim$1-100 nm for accelerated bunch.

? **The beam loading restriction to the total number of trapped electrons:**

$$N_b << 3 \times 10^7\, l_p [mm].$$

General formulae for LWFA

– **The wavebreaking field:** E_{WB}[V/cm]≈0.96(n_p[cm^{-3}])$^{1/2}$, E_{WB}≈0.68 GeV/cm for n_p≈5×10^{17} cm^{-3}.

– **The detuning length:** $L_{det}=l^3_p/l^2_L=l_p\, g_g^2$, for example, L_{det}=7.5 cm when l_p=30 mm and and g_g=50.

– **Plasma wavelength:** l_p[mm]≈3.36×10^{10}/(n_p[cm^{-3}])$^{1/2}$.

– **Plasma concentration:** n_p[cm^{-3}]≈1.13×10^{21}/(l_p[mm])^2

– **Laser field:** E_L[TV/m]≈3.2a_0/l_L[mm]; a_0≈8.6×10^{-10} l_L[mm](I_0[W/cm^2])$^{1/2}$;

$I_0=(pc/2)(m_e c^2 a_0/e\,l_L)^2$≈1.35×10^{18}($a_0/l_L$[$m$m])^2 W/cm^2; I_0≈8.4×10^{18} W/cm^{-2} when a_0=2 and l_L=0.8mm.

– **Peak power:** $P=pr^2_0 I_0/2$; P[GW]≈21.5($a_0 r_0/l_L$)^2; P≈2.15 TW when a_0=2 and r_0/l_L=5.

– **Critical power for self-focusing:** P_c[GW]≈17.4(w_L/w_p)^2=17.4(l_p/l_L)^2.

– **The Rayleigh length:** $Z_R=pr_0^2/l_L$; Z_R≈0.3 mm for r_0/l_L=10 and r_0=10 mm.

– **The laser pulse energy:** W_L~Pt_L; W»0.1 J when P=2 TW and t_L=50 fs.

The energy of a Gaussian laser pulse ($a=a_0\exp[-(z/s_z)^2]\exp[-(r/s_r)^2]$):

$W_L=[(p/2)^{1/2}/16]s_r^2 s_z(m_e^2c^2w_L^2a_0^2/e^2)=(p/2)^{3/2}s_r^2 s_z I_0/c$; W_L≈9×10^{-5} $s_r^2 s_z a_0^2/l_L^2$ J; $s_{z,r}$, l_L are in microns.

– **e-bunch energy gain:** $DW_b=N_b m_e c^2(g-g_0)\approx N_b m_e c^2 g$, g_0 is the initial gamma factor.

– **The energy of excited laser wakefield:** W_w~$[a_0^4/(1+a_0^2/2)]s_r^2E^2_{WB}L_{prop}/200$,

L_{prop} is the laser pulse propagation distance in a plasma.

$\boldsymbol{W_w/W_L}\approx[4(p/2)^{1/2}]^{-1}[a_0^2/(1+a_0^2/2)]L_{prop}/L_{det}$<<1.